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NbTi Reference Wire measurements at FNAL for Inter-Lab Comparison

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Abstract: This report summarizes the measurement of two NbTi reference samples from 02R00056A01UX.265 obtained from CERN. The first sample was measured in the 14 T test facility. The latter was measured in both the 15 T and the 14 T test facilities.

Introduction

This report summarizes critical current measurements that were made on two NbTi reference wires (sample *a* and *b*) provided by CERN for inter-lab comparison. The measurements of sample *a* were made in the 14 T/ 16 T test station. The measurements of sample *b* were made in both the 14 T/ 16 T and the 15 T/ 17 T test stations. Both test stations are equipped with anti-cryostats called Variable Temperature Inserts (VTI) that are fed in Helium from the main cryostat bath by means of a needle valve. For all measurements, the I_C is corrected for the sample temperature and results are quoted at 4.222 K. The sample temperature is measured with a Lakeshore 218 Temperature Monitor and a Cernox temperature sensor placed underneath the Ti-alloy sample holder as shown in Fig. 1. A "linear T" type of correction is applied for temperatures different from 4.222K:

$$I_C = I_t * [T_C(B) - 4.222] / [T_C(B) - T]$$

where $T_C(B)$ is the transition temperature at the specified magnetic field, I_t is the critical current measured at temperature T, and I_C is the critical current at 4.222K. $T_C(B)$ is given by [1]:

$$T_C(B) = 9.2 * \left[1 - \frac{B}{14.5}\right]^{0.59} \quad (1)$$

I_C is defined using both the resistivity criterion of 10^{-14} Ω·m and the 10^{-5} V/m electric field criterion.

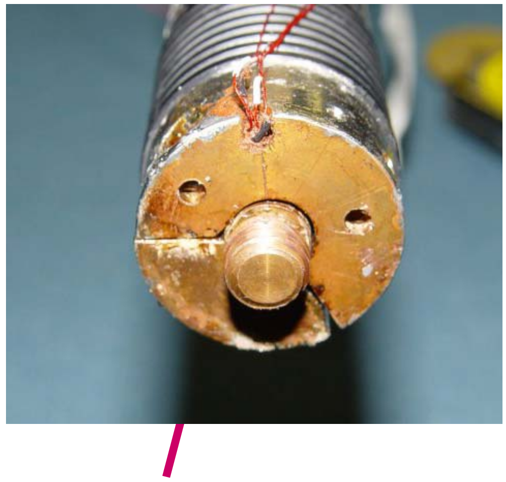

Fig. 1. Cernox location.

Samples Tested

The reference wire ~ 20 m long is a LHC cable 2 strand designated **02R00056A01UX.265** that was sent by CERN in July'06. Typical parameters for the wire are the following: wire diameter 0.825 mm, Cu/Sc ratio 1.95, filament diameter 6 µm, and an $I_C > 387$ A at 6 T [2].

Test Stations

The SC R&D Lab at Fermilab is equipped with two independent test stations. Both cryostats and solenoids are Teslatron systems made by Oxford. The 15 T/ 17 T one has a solenoid bore of 64 mm, the 14 T/ 16 T one has a solenoid bore of 77 mm. Fig. 2 shows a drawing, and Table I the characteristics of the two superconducting solenoids. In both cases, the manufacturer's quoted transfer function is being used to set the field of the magnet. To measure the signals from the voltage taps, Test Station 1 is equipped with a Keithley 706 scanner and a Keithley 182 Voltmeter with a minimum resolution of 1 nV. Test Station 2 is equipped with a Keithley 2001 digital multimeter with a minimum resolution of 10 nV.

	Test Station 1	**Test Station 2**
Maximum central magnetic field at 4.2K	15 T	14 T
Maximum central magnetic field at 2.2K	17 T	16 T
Current for full 4.2K field	102.789 A	101.004 A
Current for full 2.2K field	116.438 A	115.433 A
Field/Current ratio	0.1464 T/A	0.1386 T/A
Magnet clear bore diameter	64 mm	77 mm
Nominal inductance	52.32 H	64.60 H

Table I. Solenoid characteristics.

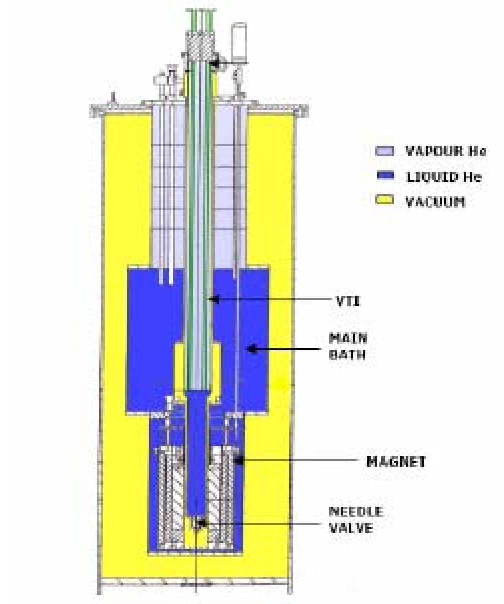

Fig. 2. Drawing of the 15T/17T test station.

Critical current measurements

The measurements are made on an "ITER-barrel" in which the wires are wound on a groove. The diameter of the center of the wire is 31.6 mm with a pinch length of 3.175 mm. Two voltage tap pairs are used over a 5 turn and a 7.5 turn section (i.e. about 50 cm and 75 cm sample length respectively).

The current I and the voltage V are recorded using the *Step-and-hold* method, that is, waiting until transient voltages have settled before taking the next data point.

The measured critical current I_C and the quality index n are then obtained by fitting the measured points using the resistive criterion (2) or the electric field criterion (3):

$$V(I) = V_{off} + R_S{*}I + I\,\rho_c\,L/A\left(\frac{I}{Ic}\right)^n \qquad (2)$$

$$V(I) = V_{off} + R_S{*}I + E\,L\left(\frac{I}{Ic}\right)^n \qquad (3)$$

V_{off}: Offset voltage caused by instrumentation
R_S: Baseline slope
ρ_c: $10^{-14}\ \Omega * \mathrm{m}$
E: 10^{-5} V/ m
L: Separation of the voltage taps
A: Strand cross section area

A typical V-I curve is shown in Fig. 3.

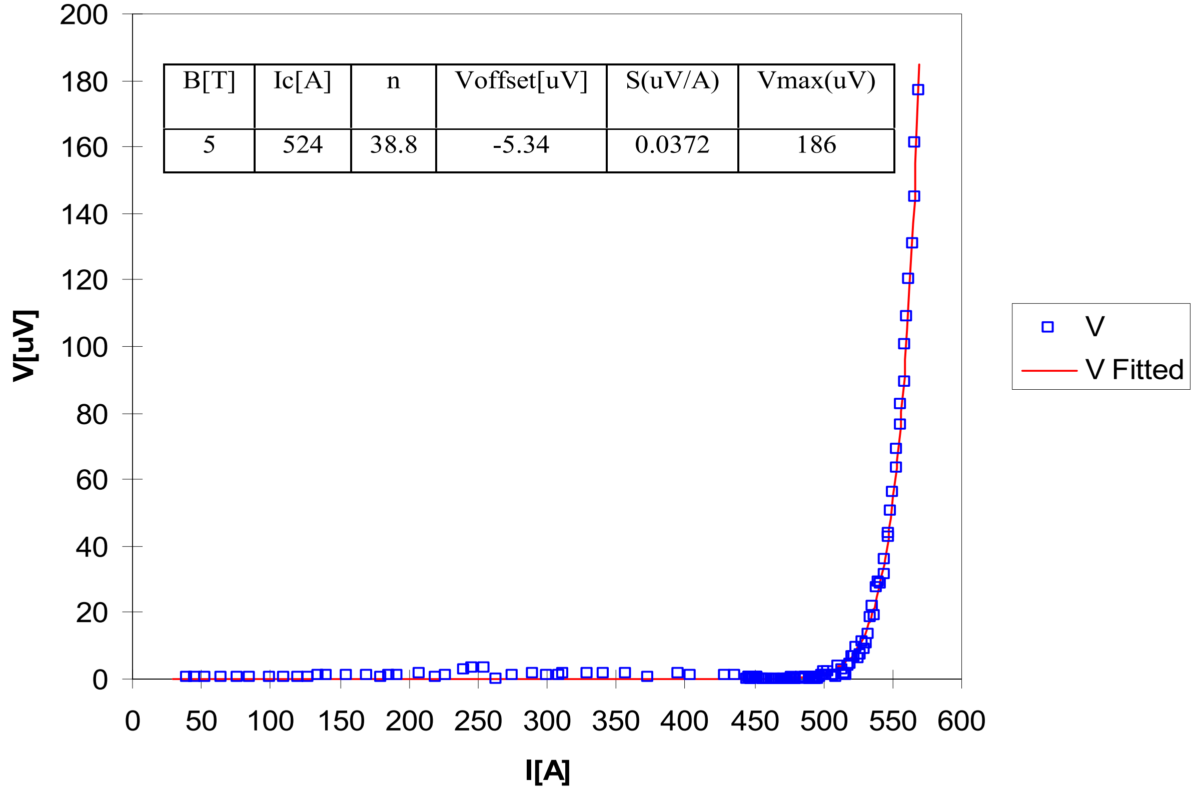

Fig. 3. Typical V-I curve (Test Station 2).

Results and Discussion

The I_C and *n*-value measurement values for samples *a* and *b* are summarized in Table II. Fig. 4 compares the I_C as a function of field between sample *a* and sample *b* when both were tested in Test Station 2. Fig. 5 compares the I_C as a function of field obtained for sample *b* when tested in Test Stations 1 and 2. Table III compares the critical currents as averaged between voltage taps obtained for samples *a* and *b* using the resistivity criterion. One can see that there is an excellent reproducibility both between the two test stations and when testing different samples within the same test station. The relative error is below 1 % as reported in columns 5 and 6 of table III except for the measurement a 9 T, possibly due to a higher level of noise during the test.

Table IV gives the average of I_C and *n*-value as measured at the test facility at CERN [3]. Comparisons of CERN and FNAL data show some discrepancy at all fields as shown in Figs. 6 and 7. The I_C values are lower than those measured at CERN by 4.7 % to 2.2 %, and the relative difference decreases with decreasing field. The solenoid transfer function yields the magnetic field in the center of the bore on both test stations. At a radial location of ~16 mm, the field is 0.33% higher. However, this would account only for a ~0.4% decrease in I_C.

	Sample *a* : 75 cm / 50 cm Test Station 2 (14 T/ 16 T) T=4.222 K				Sample *b*: 75 cm / 50 cm Test Station 1 (15 T/ 17 T) T=4.222 K				Sample *b*: 75 cm / 50 cm Test Station 2 (14 T/ 16 T) T=4.222 K			
	$10^{-14}\Omega\cdot$m			10^{-5} V/m	$10^{-14}\Omega\cdot$m			10^{-5} V/m	$10^{-14}\Omega\cdot$m			10^{-5} V/m
B[T]	I_Q[A]	I_C [A]	*n*	I_C [A]	I_Q [A]	I_C [A]	*n*	I_C [A]	I_Q [A]	I_C [A]	*n*	I_C [A]
9	123	89 / 91	17 / 21	99 / 99	120	92 / 92	21 / 20	100 / 101	124	90 / 89	17 / 16	100 / 89
8	226	191 / 192	25 / 32	199 / 200	225	191 / 193	25 / 27	200 / 200	230	193 / 193	27 / 28	200 / 199
7	340	302 / 302	35 / 36	307 / 309	339	303 / 303	35 / 35	307 / 308	343	303 / 301	34 / 31	307 / 306
6	453	411 / 411	39 / 39	413 / 413	452	412 / 414	36 / 38	415 / 416	456	413 / 413	37 / 37	416 / 416
5	569	524 / 523	42 / 41	524 / 523	568	526 / 527	41 / 42	526 / 527	570	524 / 523	38 / 39	525 / 524
4	689	641 / 640	40 / 40	640 / 640	691	644 / 647	41 / 43	641 / 644	697	644 / 644	40 / 40	641 / 641
3	832	784 / 786	42 / 42	780 / 779	847	788 / 787	41 / 40	781 / 780	847	785 / 785	38 / 38	778 / 777
2					1064	988 / 991	37 / 37	975 / 978	1020 PSL	997 / 996	[51 / 47]	985 / 983
1					1479	1383 / 1385	[34 / 33]	1353 / 1353				

Table II. FNAL Test Results.

B[T]	**Sample *a* TS2** **I_C[A]**	**Sample *b* TS1** **I_C[A]**	**Sample *b* TS2** **I_C[A]**	**Sample *b*** **(I_C(TS1)-I_C(TS2))/(Avg I_C)**	**Test Station 2** **I_C(Sample *a*)-I_C(Sample *b*) /(Avg I_C)**
9	90.0	92.0	90.5	1.64 %	-0.55 %
8	191.5	192.0	193.0	-0.52 %	-0.78 %
7	302.0	303.0	302.0	0.33 %	0.00 %
6	411.0	413.0	413.0	0.00 %	-0.49 %
5	524.0	526.5	523.5	0.57 %	0.10 %
4	641.5	645.5	644.0	0.23 %	-0.39 %
3	785.0	787.5	785.0	0.32 %	0.00 %
2		989.5	996.5	-0.70 %	

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Table III. Comparison between average I_C results (resistivity criterion) obtained for samples *a* and *b* when tested in Test Stations 1 and 2.

	4.222K, 8T	4.222K, 7 T	4.222K, 6 T	4.222K, 5 T	4.222K, 4 T	4.222K, 2.5 T
Avg Ic[A] / n	201.7 / 35	313.6 / 43	426.2 / 48	538.8 / 52	657.6 / 55	871.1 / 50
σ Ic[A] / n	1.7 / 2	1.9 / 3	2.1 / 3	2.5 / 3	2.9 / 4	0.0 / 0
σ Ic[%]	0.9	0.6	0.5	0.5	0.4	0.0
Max Ic[A]	209.4	318.9	432.2	545.3	664.3	871.1
Min Ic[A]	196.5	305.9	418.4	531.9	648.8	871.1
(Max-Min)/Ic[%]	6.4	4.1	3.2	2.5	2.4	0.0
Cooldowns / Runs	1582 / 1582	1584 / 1584	1647 / 1649	238 / 239	236 / 236	1 / 1

Table IV. CERN Test Results.

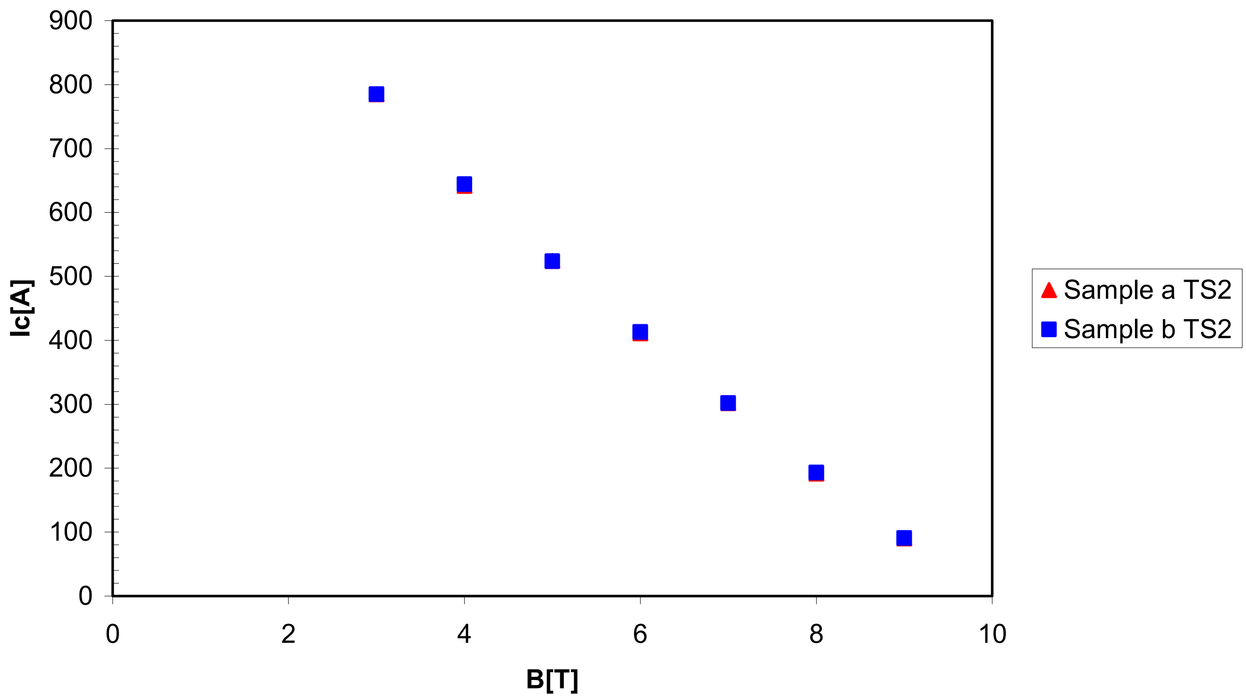

Fig. 4. Comparison between sample *a* and sample *b* when both were tested in Test Station 2.

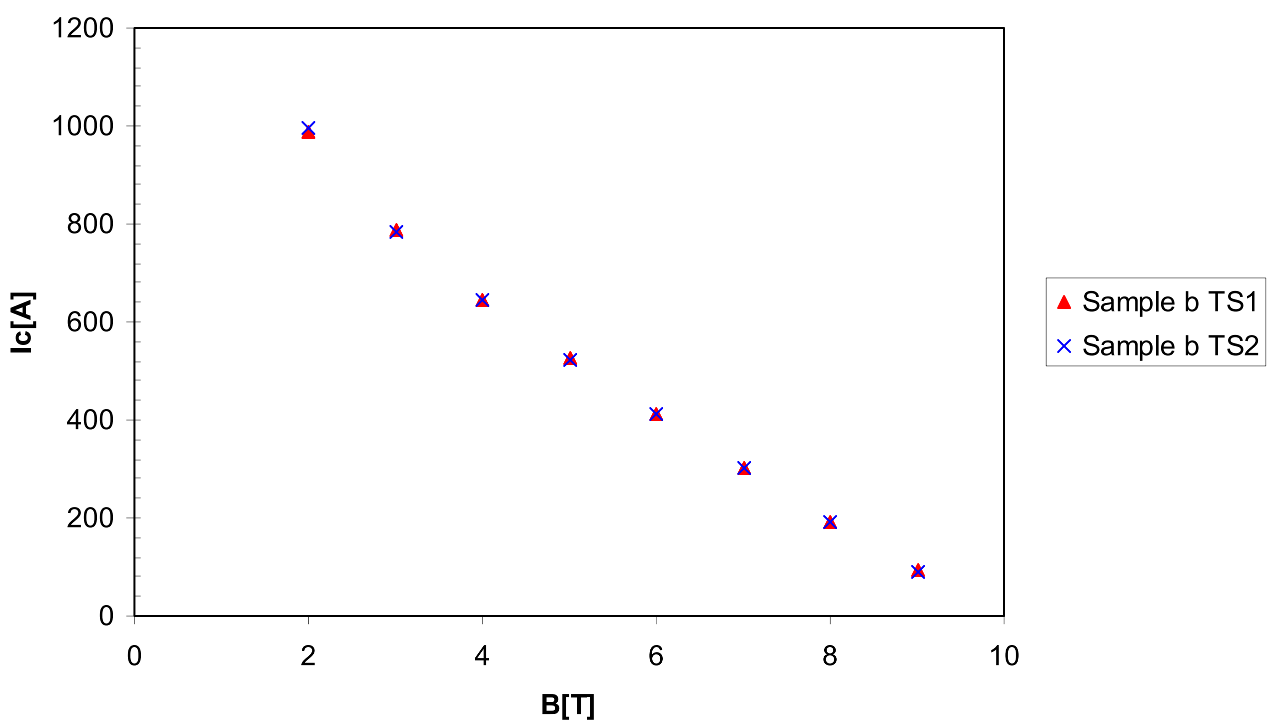

Fig. 5. Comparison between results obtained for sample *b* when tested in both Test Stations 1 and 2.

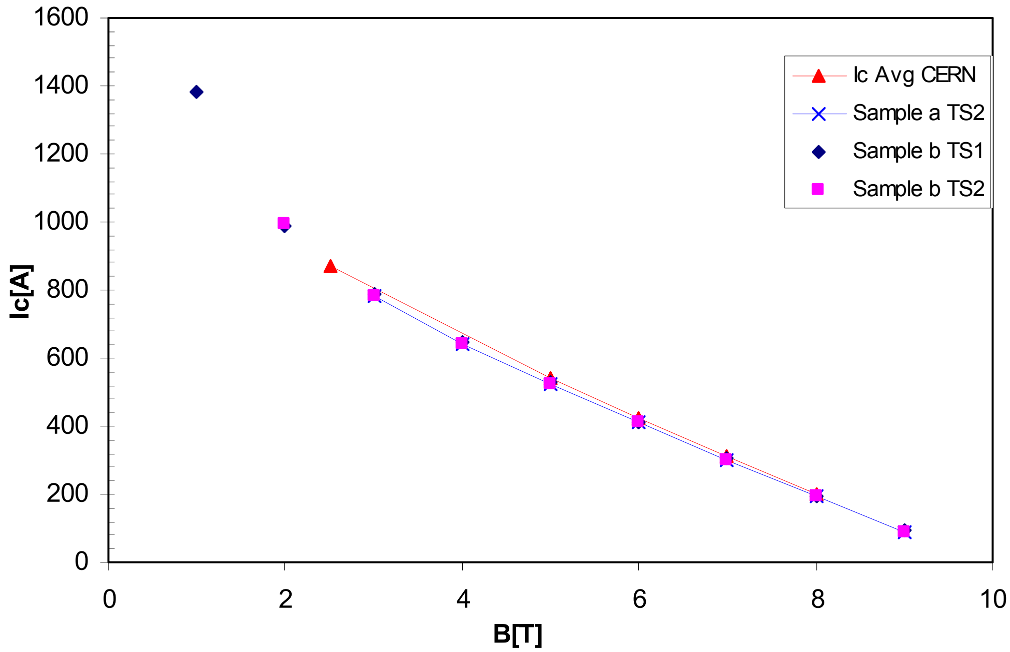

Fig. 6. Comparison between CERN average data and the FNAL tests.

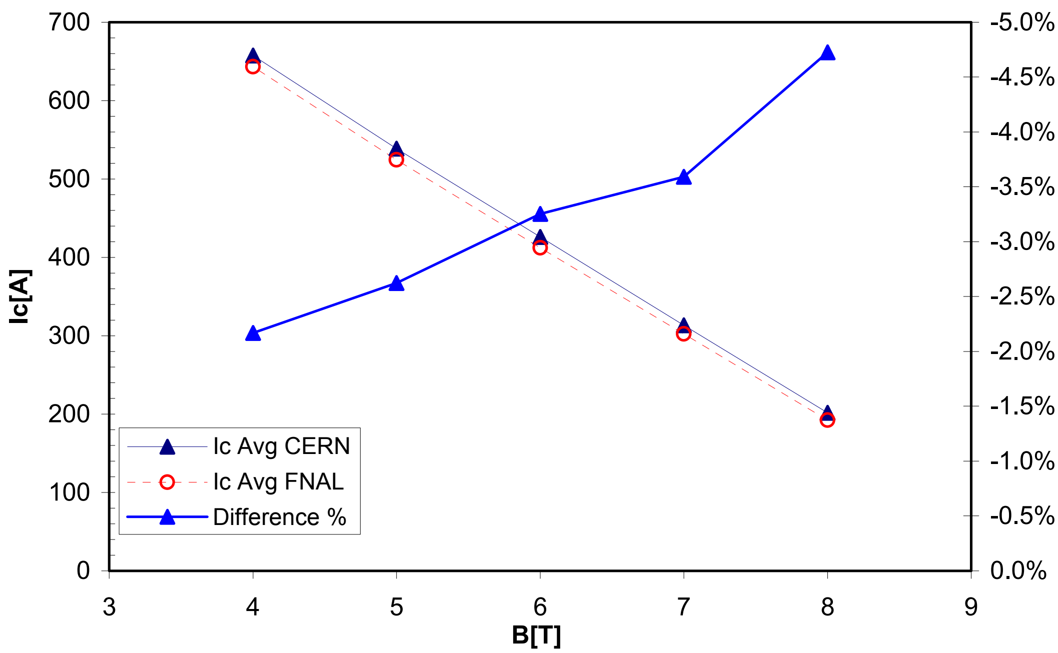

Fig. 7. Comparison between CERN average data and FNAL average data.

References

1. “Empirical scaling formulas for critical current and critical fields of commercial NbTi”, M. S. Lube11, *IEEE Trans. on Magnetics*, Vol. Mag-19, No. 3, 1983.
2. “NbTi CERN Reference wire measurements at BNL”, A. K. Ghosh and E. D. Sperry, BNL Magnet Division Note, AM-MD-349, 2007.
3. CERN data were provided by T. Boutboul, "Thierry Boutboul" Thierry.Boutboul@cern.ch.